



Where do we go from here?

Dallas/Ft Worth DER Conference May 24-24, 2006

Anthony A. Lambregts

FAA Chief Scientific and Technical Adviser for Flight Guidance and Control Tony.Lambregts@FAA.gov

Overview



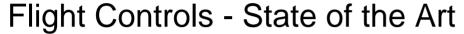
- Flight Controls State of the Art
 - General Aviation
 - Transport Airplanes
- Safety
 - incident and accidents
 - Regulations Updates
- Technology Trends
 - Advanced Controls & Displays
 - Fly By Wire
- Research
 - TCRG (Technical Community Representatives Group)
 - completed, in progress,

General Aviation

Flight Controls - State of the Art

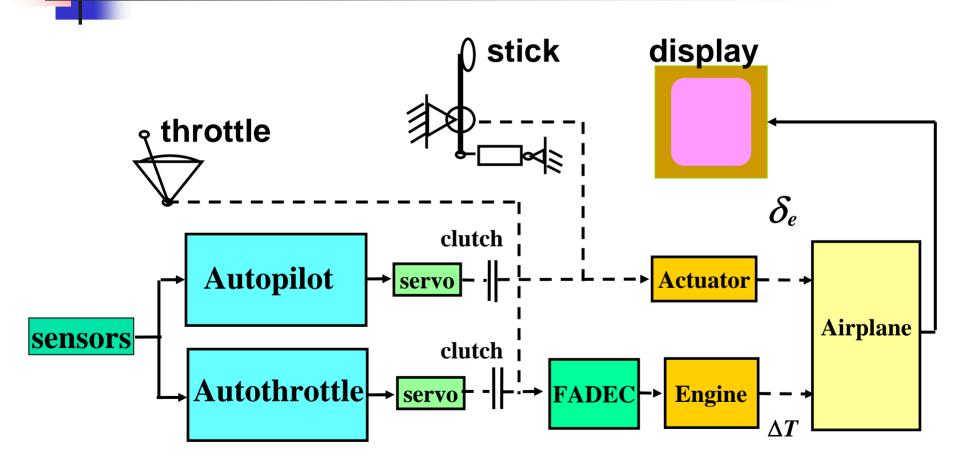
- basic technology
 - manual and automatic controls designs fairly static
 - basic mechanical controls, no FBW
 - basic autopilot modes, no autothrottle
- current developments focused in avionics piloting aids
 - flat panel PFD, MFD
 - Nav Aids: GPS/WAAS/RNAV; TAWS, ADS-B Flight Inf, Air Traffic, Weather Info; e.g. Capstone program, Alaska
 - MFD Terrain Displays
 - PFD Flight Path Vector, 3-D Pathway in the Sky → Synthetic Vision (3-D-terrain)
- ISSUES: piloting skills (stalls, loss of control, CFIT), equipment failures, entering Instrument Meteorological Conditions without proper equipment and skills

Transport Airplanes



- Technology
 - manual control → slowly moving to FBW
 - slow acceptance of embedded Envelope Protection
 - automatic controls designs
 - traditional SISO autopilot, autothrottle, FMS modes
 - new programs: design updates to comply with new Regs
 - little or no movement toward advanced integrated design
- Avionics slow developments in Integration of Functions
 - PFD, MFD displays, e.g.
 - Vertical Profile displays
 - PFD Flight Path Vector display
 - NAV Aids: GPS/WAAS/RNAV/GLS; Baro VNAV, TAWS,
 - Data Link applications: Flight, Air Traffic, Weather Info

State of the Art Flight & Propulsion Control Transports





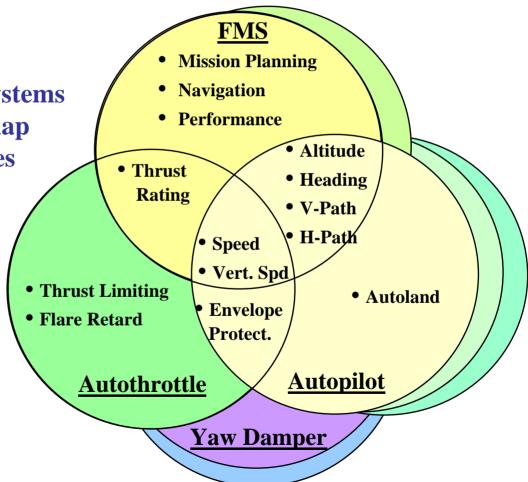
Transport Airplanes

Flight Controls – ISSUES

- Automatic Controls:
 - complexity, mode confusion
 - man-machine interfaces
 - control authority limiting; mode annunciation/alerting
 - Envelope Protection (n_z, AOA, Airspeed, Bank Angle)
 - single axis SISO versus integrated MIMO control modes
- Manual control
 - piloting skills, Handling Q & control authority (AA 587 rudder)
 - stalls, upsets, recovery
 - need for maneuver rate, load limit, protections
- Manual & automatic control interaction/transitioning
 - Loss Of Control, Upset Recovery
- FBW augmented manual control still in its infancy....

Typical Transport Airplane Flight Guidance & Control System as many as 8 LRUs

- highly complex designshistorically evolved subsystemsextensive functional overlap
- operational inconsistencies
- incomplete envelope protection
- SISO control
- <u>little or no</u> <u>standardization</u>





Typical FG&C related Incidents and Accidents

- Pilot fails to monitor autopilot operation (Mexicana DC10) Autopilot stalls airplane
- A/P roll control saturation, engine out (China Airlines B747)
- unexpected high altitude automatic disengage, out-of-trim, pilot over controls (MD11)
- imperceptible airplane slow roll response, due to A/P sensor failure without proper alert (Evergreen 747)
- A/P reaches roll authority limit in icing, / disconnects without timely warning, stall (Embrair Comair, Detroit)
- Pilot tries to take manual control, A/P remains engaged, overrides pilot (China Airlines A300, Nagoya)
- Pilot over controls rudder, after mild Wake Vortex encounter. Vertical Stabilizer fails (AA 587, New York)



Summary of New Requirements in FAR 25.1329

FAR/AC covers of Autopilot, Autothrust and Flight Director (not FMS)

- engage/disengage/ mode switching transients
- incompatible FGS modes should be avoided
- warning/alert for autopilot and autothrottle disengage
- logical man-machine interfaces to minimize crew confusion and errors
- Vertical Modes preferred operational characteristics
 - Vertical Speed and Flight Path Angle modes
 - Altitude Acquire or Flight Level Change mode
 - Altitude Hold mode



Summary of Updated Guidance AC 25.1329 (cont'd)

Vertical Modes should:

- operate to ATC provided targets (Alt, Vert Spd, Airspeed)
- smoothly capture Altitude & Vert. Spd, with limited normal acceleration
- provide tie-in with speed envelope protection
 - also when autothrottle engaged
- not exhibit unacceptable control transient when changing the Reference Pressure or Altitude Select window setting
- not fail to capture target altitude when changing Altitude Select window setting
- Altitude Hold: should smoothly reduce vertical speed to zero, then hold altitude, or return to engage altitude



Summary of Updated Guidance AC 25.1329 (cont'd)

- Pilot Override of Autopilot / Autothrottle must not result in unsafe condition:
 - significant override force should disconnect autopilot
 - automatic trimming in opposition to pilot input prohibited
 - prevent "jack knifing" elevator/stabilizer
 - trim on elevator position, not stick force
- Control Wheel Steering mode that provides manual control through autopilot is discouraged
 - subject to autopilot authority limits (serious limitation!)
 - satisfactory Handling Qualities must be demonstrated for all intended flight conditions (probably impossible)
 - best avoided where full authority control may be needed (e.g. take off, landing, windshear, stall recovery)

Summary of Updated Guidance AC 25.1329

- speed envelope protection
 - help distracted pilots refocus attention in safety critical situations
 - as a minimum the FGS must provide
 - \bullet aural and visual alert for low speed, e.g. IAS < 1.2 V_{stall}
 - visual alert high speed, e.g. $IAS > V_{MO}/M_{MO}$
 - FGS may provide automatic protection against excursions outside normal flight envelope, e.g.
 - Autothrottle "wake up" (may not be adequate!)
 - revert from path mode to speed protection, or
 - disengage + provide warning
 - nuisance mode reversions and alerts should be minimized, especially on approach

Envelope Protection Functions

- Objective: safeguard against airplane entering into unsafe condition
- Airspeed: keep between Vmin and Vmax
 - by limiting IAS_{cmd}
 - by control priority: requires mode switching & crew alerting
 - solution can get very complex in traditional systems
- Normal Load Factor (n_z):
 - automatic modes: $|n_z|$ < .1 for passenger comfort
 - FBW manual mode:
 - $0 < n_z < (n_z)_{\text{structural limit}}$
 - low speed: $n_z < (n_z)_{\alpha-limit}$; $(n_z)_{\alpha-limit} = (Ve/Ve_{stall-1g})^2$
- Angle of Attack (α) limit: implicit if n_z and Airspeed protected
- Bank Angle: bank limit depends on mode & flight condition
- Sideslip (β) limiting: possible in some FBW manual designs



- Single axis SISO automatic control modes have been the standard since earliest days of automation
 - It works.... most of the time
 - accommodated the peace meal additions of new modes
 - root-cause of most automation complaints
 - unlike pilot control strategy, which is multi-axes
 - command tracking errors due to control coupling
 - poor damping, high control activity, inconsistencies
 - mode proliferation & complexities, pilot confusion
 - not dependable: can cause loss of control
 - requires full time pilot monitoring!
- SISO design deficiencies and limitations can be effectively overcome by going to Multi Input/Multi Output (MIMO) design

Further FG&C System Safety & Cost of Ownership Enhancements

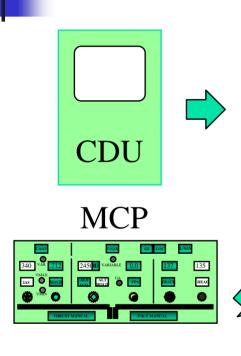
Must come from introduction of Standardized Reusable Design, using

- Large scale function consolidation & integration
 - Multi-Axes MIMO control strategy
 - no function overlap minimum sensor set; less software
 - over-arching safety features full envelope protection
- Fault tolerant architectures (deferred maintenance)
 - fewer LRUs function co-hosting
 - all functions fully monitored
 - all digital data communications less aircraft wiring
- Design commonality across many airplane types
 - less customization
 - common type rating less flight crew training
 - smaller development/validation effort less flight testing

Advanced Functionally Integrated Multi-Axes MIMO Control

- Traditional Automatic FG&C systems have contributed in a major way to improving flight safety, in spite of their shortcomings
- Future MIMO functionally integrated FG&C designs can enhance safety and operational effectiveness through
 - all-encompassing pilot-like control strategy for all modes
 - automatic
 - augmented manual
 - fewer/less complex modes, operationally consistent
 - up-front integrated
 - more intuitive man-machine interfaces
 - simpler envelope protection, built into Core algorithm
 - priority control, serving all modes
 - advanced Heads Down displays (e.g. SVS Terrain, HITS, FPA symbology)

Simplified FG&C System Architecture



- Rational Function Partitioning
- No Function Overlap
- Common Control Strategy
- Simplified Reusable Design

FMC

Flight planning

- Navigation
- Path Definition
- Performance Predict.

Strategic
Airline Operations
Oriented Functions



- Airspeed/ Mach
- Altitude/Vertical Spd
- Heading/Track
- Loc / GS, V-Nav / L-Nav
- Envelope Protection
- FBW Manual Mode

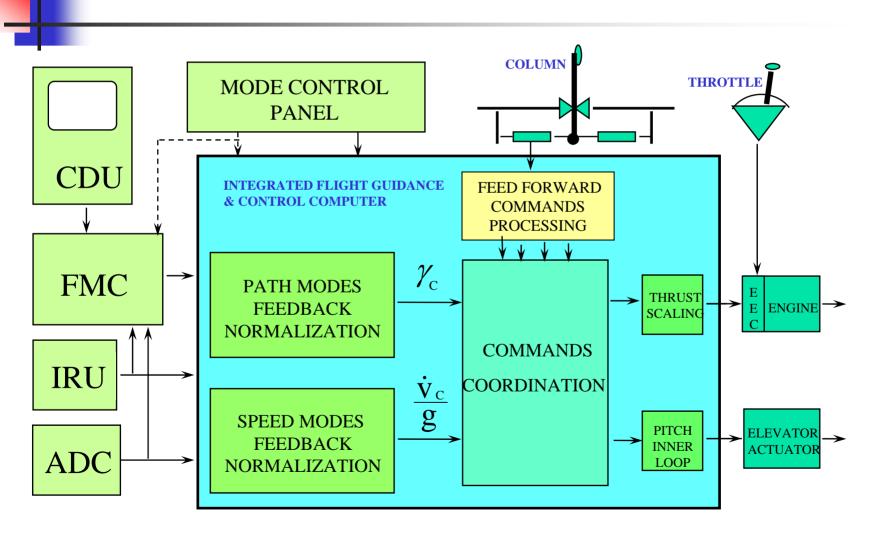
Tactical Automatic & FBW augmented manual Control Modes and Safety Functions

The Good News

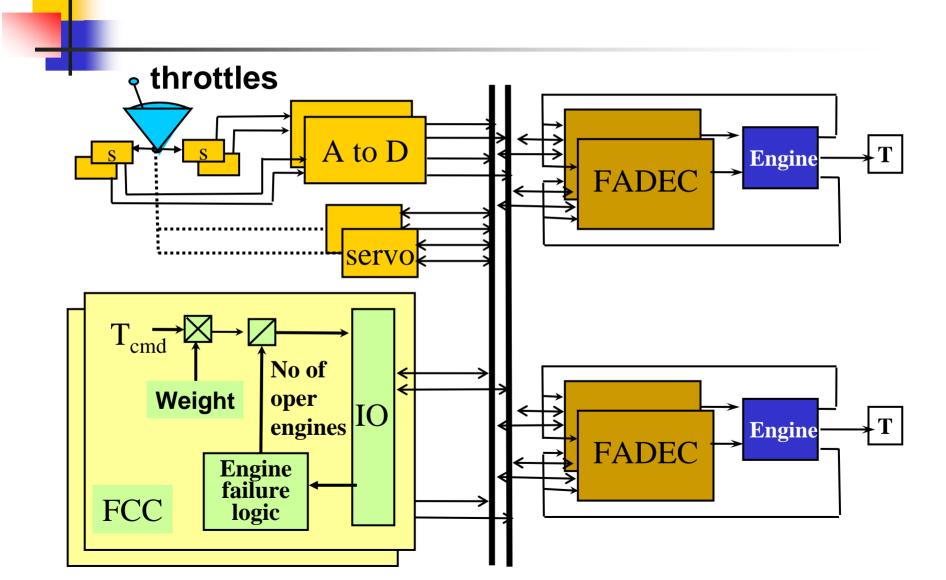
- Generalized MIMO FG&C Systems with all the discussed attributes already exist:
 - Total Energy Control System (TECS), developed under NASA / Boeing TCV program in the early eighties
 - Energy based MIMO Flight Path & Speed Control Concept
 - extensive Pilot-In-The-Loop simulator evaluations (1989-1985)
 - Validated by Flight Test & In-flight demonstrations (1985)
 - Total Heading Control System (THCS), developed under DARPA/ Boeing Condor program (1985-1990)
 - Full set of Integrated Lateral-Directional Control functions
- a lot of low cost COTS hardware is available
 - integrated sensor packages
 - standard computing and interface resources

First 10 % of design decisions lock in 90% of systems cost

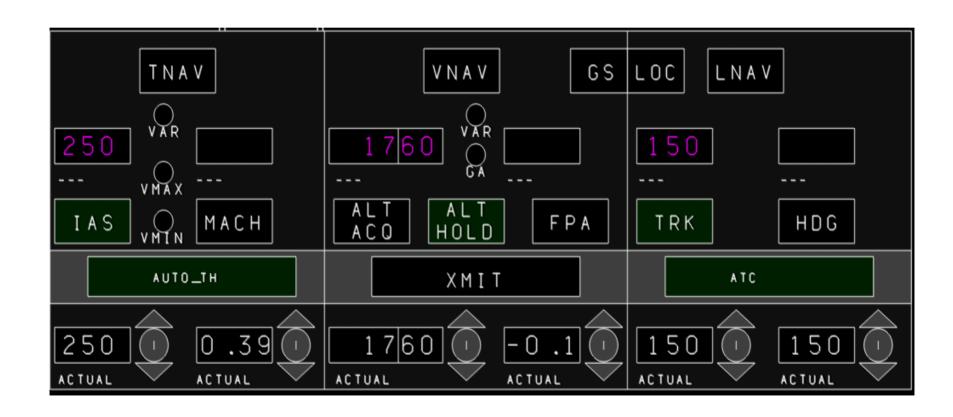
Functionally Integrated Automatic and Manual FBW Control



Digital FCC / Throttle /FADEC Interface Concept



TECS/THCS Mode Control Panel Concept with Integrated ATC data link Functions





Impediments to Application of Advanced FG&C in GA

- GA aircraft suffer from relatively much higher accident rate than commercial transport, due to
 - lower pilot skills
 - unexpected encounter of challenging flight conditions
 - poor systems reliability, maintenance deficiencies
- GA aircraft can therefore benefit most from applying advanced
 FG&C technology, but cost is believed to be prohibitive
 - redundant system architecture
 - hardware
 - software development

.... but hold on.....

Eliminating Application Barriers to Advanced Integrated FG&C Systems

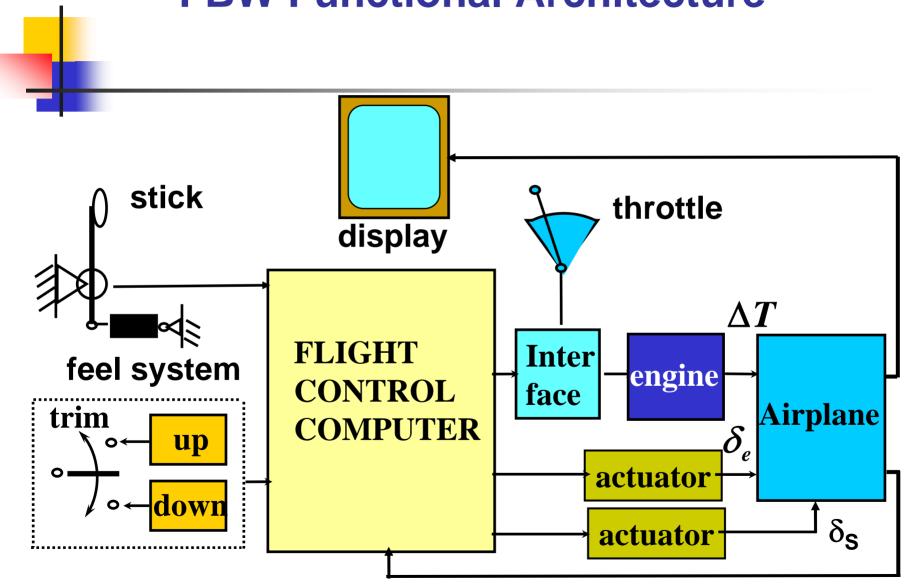
- Perceived risks of Change-Over need to be addressed
 - Full operational assessment: issues
 - operations procedures
 - flight crew acceptance
 - Automation by level rather than by individual axis
 - possible flight crew retraining impact
 - Full safety benefits assessment: issues
 - effectiveness of New man-machine interfaces
 - envelope protection functions
 - Design application risk assessment: issues
 - design operational suitability & flight crew acceptance
 - certification requirements/effort;
 - impact of design changes on company's competitive position
 - Cost benefit analysis

Fly-By-Wire Design



- Definition: Airplane control concept whereby surfaces commanded through electrical wires
- Sought benefits:
 - Weight reduction
 - Lower maintenance
 - Design freedom to optimize aerodynamic performance by RSS and achieve standardized handling qualities through SAS and CAS
 - Cost reductions
 - Reduced pilot training (common type rating)
 - Design commonality/design cycle time reduction

FBW Functional Architecture





FBW Design Opportunities

- simplify operations concept
- simplify hardware architecture and design
 - shedding historically accumulated "baggage",
 e.g. design features typically belonging to previous generations of technologies:
 - complex feel systems
 - column, wheel back-drive systems
 - stick shaker, stick pusher
 - individual actuator loop closure Force Fight
- Instead of designing Band-Aids to make it possible for the pilot to live with the vagaries in the system, the FBW system should eliminate these vagaries (and Band-Aids)



- Controllers Column & Wheel versus Sidestick
- Feel system Passive (e.g. spring) or Active (expensive !)
- Control augmentation Algorithm response type
 - simple or none little or no HQ advantages
 - stability/command substantial benefits possible
 - more complex/costly many issues
 - Handling Qualities: what HQ, how best achieved
 - envelope protection major safety benefit!
 - Good design enhances pilot control authority
 - mode changes takeoff/landing
- Actuators: loop closure, e.g. central or remote loop closure
- Redundancy architecture & component reliability

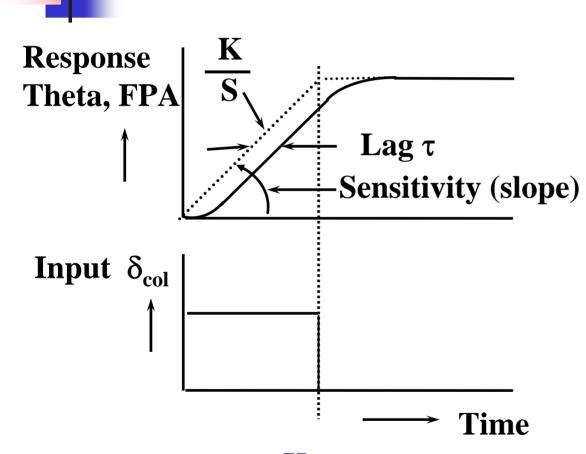




Definition: The conglomerate of characteristics and features that facilitate the execution of a specific flight control task; includes display and feel characteristics

- good HQ requires design attributes appropriate to control task (e.g. pitch attitude, FPA, or altitude control)
- each task has a finite time allotment or expectation for its completion (bandwidth requirement)
- direct control of "slow variables" requires special design attributes (e.g.FPA response augmentation & display)
- control harmony is achieved when the pilot can execute the task without undue stress and conscious effort

FBW Control Response Attributes for Good HQ



Desired Attributes:

- "K/S"- like response
- low response lag τ
- correct sensitivity K
- good damping
- no overshoot
- control harmony with other variables (θ, γ, n_z)
- consistency between flight conditions

NOTE: signal $\frac{K}{S}$ δ_{col} can serve as the cmd reference

FBW Control Algorithm Types

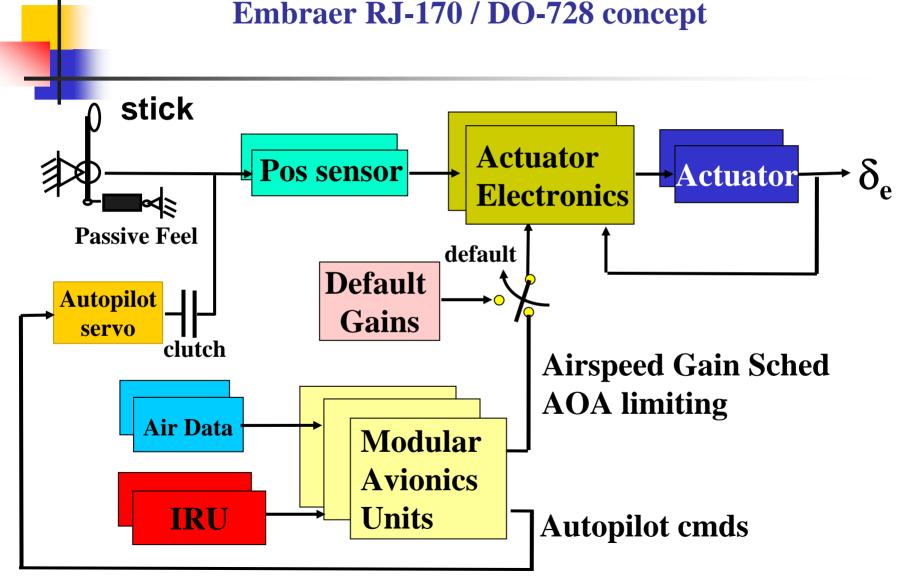


- pitch attitude rate command (+ pitch attitude hold)
- n_z-command
 - proportional angle of attack (AOA) command
 - C*= n₂ command / Vertical Speed hold
 - FPA rate command / FPA hold
- Roll: roll rate command / roll attitude hold
 - + heading or track hold for bank angle < X°
- Yaw: sideslip command proportional to pedal

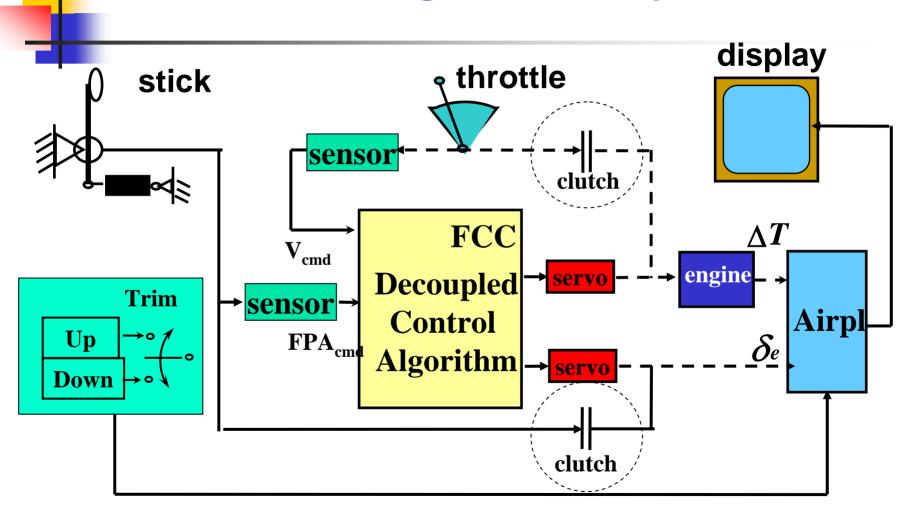
Given sufficient know-how, all of these concepts can be made to perform well: the devil is in the details!

Basic FBW System Example

Embraer RJ-170 / DO-728 concept



Raytheon Low Cost GA FBW Concept Bonanza Flight Demo System



• Stick commands proportional FPA; Throttle commands speed

Rationale For Low End GA FBW

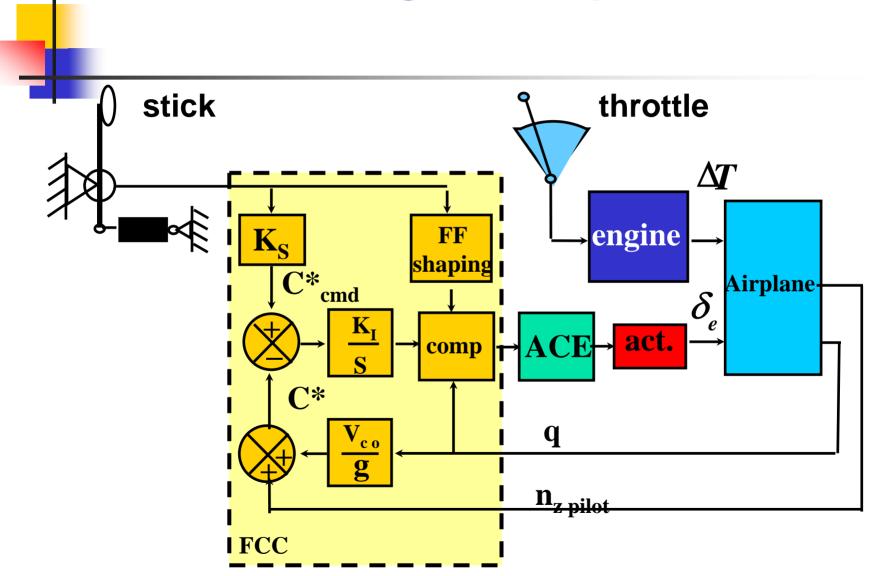


- Eliminate most low pilot skill related accidents
 - stall, spin
 - Loss of Control due to spatial disorientation
 - Lack of IMC flight skills (inadvertent weather)
- Accept new FBW system related accidents, but lower overall rate

Approach:

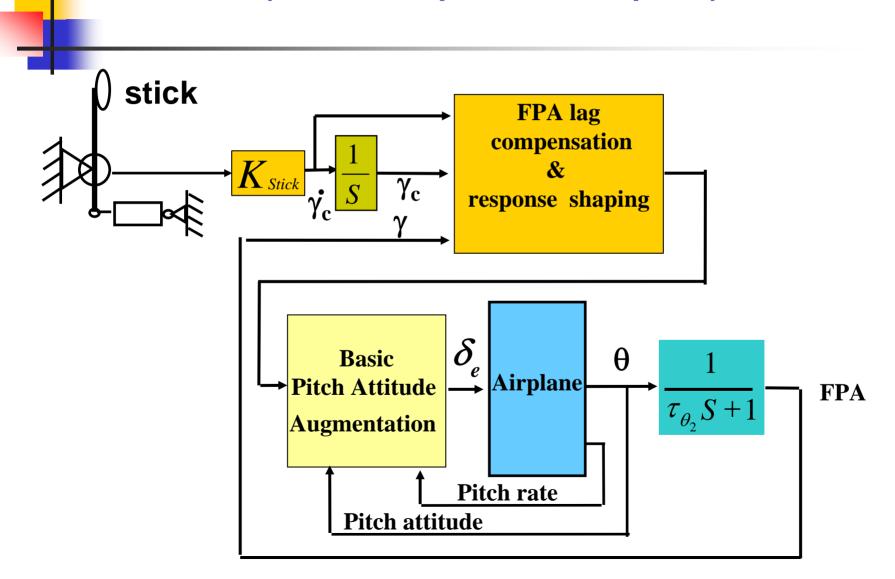
- embedded envelope protection functions
- low cost FBW design strategy:
 - simple control algorithm
 - simple high reliability components
 - dual sensor set, computer and data bus
 - basic redundancy and FDIR strategies, e.g.
 - single servo on split surfaces

C* Design Concept



FPA Control Algorithm

(Constant speed assumption)





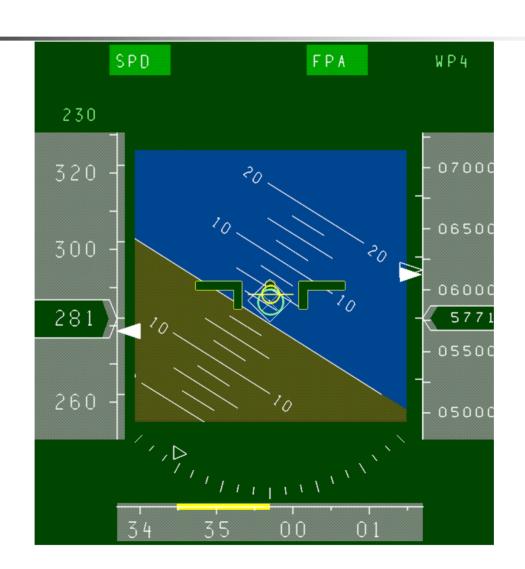
Making FBW Pay

- FBW should make sense /cents:
 - use the opportunity to achieve realizable advantages
 - simpler/reusable design; reduced weight/maintenance
 - consistency between manual and automatic control
 - enhanced performance & safety
- Generalized/Integrated Flight and Propulsion Control provides
 - consistency between manual and automatic operations
 - Flight Path Angle based design can provide superior control
 - excellent/uniform Handling Qualities
 - reduced pilot workload, e.g. during continuous descent
 - maintains established flight path angle, regardless of disturbances, speed, configuration changes
 - consistent with HUD
 - easy to embed envelope protection functions

Needed Flight Guidance and Control Research

- Pilot-in-the-Loop Rudder Control System Requir. (AA FL 587)
- Generalized Functionally Integrated FG&C
 - Assessment of Safety Improvements and Operational Effectiveness to eliminate application barriers (with NASA)
 - Simpler, more intuitive man-machine interfaces
 - Low cost General Aviation applications to reduce CFIT and LOC
 - UAV FG&C systems Operational & Certification Requirements
- FBW control technologies and certification regulations
 - Side stick, feel system, display requirements; IPs, SCs
- Advanced FG&C and FBW Systems Architectures & Design Assurance
- Integrated FG&C Displays
- Reduction of Turbulence Induced Aft Fuselage Accelerations

Advanced Displays



FAA Flight Controls TCRG





Flight Controls TCRG was formed to effectively address FAA need for flight controls related research

- certification related issues
 - form consensus and prioritize research task
 - provide voice in FAA research funding process

started with Transport Directorate representatives

- Robert C. Jones chair; members:
 - Anthony A. Lambregts CSTA Advanced Controls
 - Archie Dillard CSTA Flight Simulation
 - Robert Mcguire ACT task manager
 - Dick Newman, Don Simpson, Loran Haworth, ANM 111
- representation to be expanded to Small Airplane and Rotorcraft Dir
 - Wes Ryan ACE 114,

Rudder Control Research Task



Phase I: (Completed)

- Pilot Survey on rudder use
- desk top computer analyses of rudder systems
 - Dr. Ron Hess U of California at Davis
 - effects of rudder control systems nonlinearities
 - multi-axes control loop closure, stability, PIO

• Phase II:

- Pilot-in-the-loop Simulation of rudder systems
 - Hoh Aeronautics in Research Task Planning process
 - Objectives: develop guidance materials for design of rudder control systems and recommendations for certification requirements, e.g.
 - breakout forces, force gradients, force/displacement limits
 - pilot use of rudder & training



Other FAA Flight Control Research

Congressionally mandated/funded research

- Centers of Excellence COE
 - National Institute for Aviation Research (NIAR) at Wichita State University
 - Advanced Control for GA aircraft
 - integrated/decoupled flight path & speed control
 - Neural Net applications: failure compensation; estimation of airplane model parameters
- Joint University Program
 - MIT, Princeton, U of Ohio at Athens, FAA, NASA
 - GPS applications
 - air traffic management
 - advanced/robust control design



Questions??